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InflateSail De-Orbit Flight Demonstration Results and Follow-On Drag-Sail Applications

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Abstract

The InflateSail (QB50-UK06) CubeSat, designed and built at the Surrey Space Centre (SSC) for the Von Karman Institute (VKI), Belgium, was one of the technology demonstrators for the European Commission's QB50 programme. The 3.2 kg 3U CubeSat was equipped with a 1 metre long inflatable mast and a 10m^2 deployable drag sail. InflateSail's primary mission was to demonstrate the effectiveness of using a drag sail in Low Earth Orbit (LEO) to dramatically increase the rate at which satellites lose altitude and re-enter the Earth's atmosphere and it was one of 31 satellites that were launched simultaneously on the PSLV (polar satellite launch vehicle) C-38 from Sriharikota, India on 23rd June 2017 into a 505km, 97.44^o Sun-synchronous orbit.

Shortly after safe deployment in orbit, InflateSail automatically activated its payload. Firstly, it inflated its metre-long metal-polymer laminate tubular mast, and then activated a stepper motor to extend four lightweight bi-stable rigid composite (BRC) booms from the end of the mast, so as to draw out the 3.1m x 3.1m square, 12μm thick polyethylene naphthalate (PEN) drag-sail. As intended, the satellite immediately began to lose altitude, causing it to re-enter the atmosphere just 72 days later – thus successfully demonstrating for the first time the de-orbiting of a spacecraft using European inflatable and drag-sail technologies.

The InflateSail project was funded by two European Commission Framework Program Seven (FP7) projects: DEPLOYTECH and QB50. DEPLOYTECH had eight European partners including DLR, Airbus France, RolaTube, Cambridge University, and was assisted by NASA Marshall Space Flight Center. DEPLOYTECH's objectives were to advance the technological capabilities of three different space deployable technologies by qualifying their concepts for space use. QB50 was a programme, led by VKI, for launching a network of 50 CubeSats built mainly by university teams all over the world to perform first-class science in the largely unexplored lower thermosphere.

The boom/drag-sail technology developed by SSC will next be used on a third FP7 Project: RemoveDebris, launched in 2018, which will demonstrate the capturing and de-orbiting of artificial space debris targets using a net and harpoon system. This paper describes the results of the InflateSail mission, including the observed effects of atmospheric density and solar activity on its trajectory and body dynamics. It also describes the application of the technology to RemoveDebris and its potential as a commercial de-orbiting add-on package for future space missions.
Keywords: (CubeSat, Drag-Sail, Active Debris Removal, Post Mission Disposal, QB50)

Acronyms/Abbreviations

ADCS	Attitude Determination and Control System
ADR	Active Debris Removal
AIT	Assembly Integration and Testing
BC	Ballistic Coefficient
BoPET	Biaxially Oriented Polyethylene Terephthalate
BRC	Bistable Rigid Composite
BST	British Summer Time
CAD	Computer Aided Design
CAN	Controller Area Network
CFRP	Carbon Fibre Reinforced Plastic
CGG	Cool Gas Generator
CMOS	Complementary Metal-Oxide-Semi-conductor
CNES	Centre National d'Etudes Spatiales
COTS	Commercial-Off-The-Shelf
CSS	Coarse Sun Sensor
DC	Direct Current
DLR	German Aerospace Centre

EKF	Extended Kalman Filter
EPC	Electric Power System
ESA	European Space Agency
EC	European Commission
EVT	Environmental Testing
FIPEX	Flux-Φ-Probe Experiment
GPS	Global Positioning System
HAL	Hardware Abstraction Layer
I2C	Inter-Integrated Circuit
IADC	Inter-Agency Space Debris Coordination Committee
IOD	In Orbit Demonstrator
INMS	Ion-Neutral Mass Spectrometer
ISIS	Innovative Solutions in Space
ISO	International Organization for Standardization
ISS	International Space Station
LEO	Low Earth Orbit
m-NLP	Multi-Needle Langmuir Probe
MEMS	Micro-Electro-Mechanical System
MSSL	Mullard Space Science Laboratory
MW	Momentum Wheel
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
OBC	On Board Computer
PEN	Polyethylene Naphthalate
PMD	Post Mission Disposal
PSLV	Polar Satellite Launch Vehicle
RTOS	Real Time Operating System
SSC	Surrey Space Centre
SSO	Sun Synchronous Orbit
SSTL	Surrey Satellite Technology Ltd.
STELA	Semi-Analytic Tool for End of Life Analysis
TeSeR	Technology for Self-Removal
TLE	Two Line Element
TNO	Netherlands Organisation for Applied Scientific Research
TRXVU	Transmitter/Receiver VHF/UHF
UK	United Kingdom
UHF	Ultra- High Frequency
UTC	Universal Time Coordinated
VCB	Valve Controller Board
VHF	Very High Frequency
VKI	Von Karman Institute for Fluid Dynamics

1. Introduction

In recent years, increasing attention has been given to the problem of space debris and its mitigation. As shown in Figure 1, a major source of new space debris is due to the break-up and fragmentation of spacecraft that remain in orbit after the end of their operational mission lifetime. Such debris is created, for example, by internal explosion (e.g. due to failure to passivate propulsion and electrical power storage systems) or when objects collide. In 2009, two satellites: Kosmos-2251 and Iridium-33 collided accidentally, producing a large quantity of debris which can be seen as a step change in the number of fragmentation objects shown in Fig. 1 [1]. The large step increase in 2007 was due to the fragmentation of the Chinese satellite FengYun-1C.

Notwithstanding such events, it is clear from the accelerating growth in space activity that the risk posed by debris to operational spacecraft can only get worse. Indeed, the probability of collisions increases exponentially with the number of objects present, and there is a significant risk that some orbits could become essentially inaccessible due to a catastrophic cascading effect – the so called Kessler syndrome [2]. As a result, regulations (e.g. ISO 24113) have been drawn-up which require the removal of spacecraft at the end of operation – known as Post-Mission-Disposal (PMD) – with a compliance rate of at least 90% to ensure that the spacecraft do not become a new source of space debris. NASA recommends that the removal process should take less than 25 years if we are to avoid catastrophe [3].

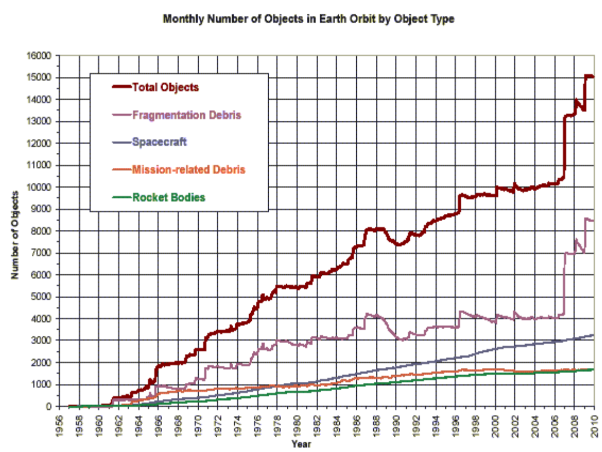

Fig. 1. Growth of the Orbital Debris Problem – NASA Orbital Debris Program Office (Objects > 10cm Diameter)

Satellites in very low altitude orbits (e.g. those below the International Space Station (ISS) at ~400km altitude) may decay from orbit naturally within the required period due to the effect of atmospheric drag acting on the spacecraft body. For other satellites in higher orbits, it is likely that some form of Active Debris Removal (ADR) technique will be necessary – either by deliberately disposing of it through destruction in the atmosphere, or by moving it into a designated “graveyard” orbit.

As a step towards this, the European Commission's (EC)'s Horizon-2020 programme is supporting the TeSeR Project [4], which has analysed the efficacy of different ADR approaches for various classes of satellite in different orbits with a view to developing a set of standard cost-effective PMD modules that can be fitted routinely to future spacecraft. The EC also supported the RemoveDebris mission, which is aimed at providing Europe's first in-orbit demonstration of "capture and dispose" techniques, thus demonstrating the technology needed to apply ADR to space objects with no pre-existing ADR capability.

For low-Earth orbit (LEO), missions (<1000km altitude), the residual atmosphere encountered in orbit offers a potentially simple and relatively low cost method of PMD through the use of deployable drag augmentation devices. These devices (e.g. sails, flaps, panels, balloons, etc.) are designed to significantly reduce the ballistic coefficient (BC) of the orbiting object by increasing the cross-sectional area it presents to the free-stream as it moves at hypervelocity along its orbital trajectory. Objects with large BCs (i.e. those with a large mass to cross-sectional area ratios) exhibit slow orbital decay, whereas those with small BCs decay more rapidly. This leads to the counter-intuitive result that "heavy" satellites fall down more slowly than "light" satellites, and, in general, "small" satellites fall down more rapidly than "large" satellites. This is because, for uniform density, mass scales as dimension cubed whereas cross-section scales only as dimension squared.

It should be noted, however, that drag augmentation is not a suitable PMD technique for every object, as larger heavier objects, depending on their make-up, may survive all the way down to the ground, and thus present a potential risk to populated areas. Also, as atmospheric drag effects are highly variable in space and time – even at constant altitude – it is not possible to use this technique to target a particular unpopulated disposal point (e.g. over the oceans). However, for many spacecraft in the "small satellite" category (<500kg mass), which are currently experiencing enormous growth in numbers, such disposal will lead to their harmless vaporization in the upper atmosphere.

Thus, the University of Surrey – Surrey Space Centre (SSC), which specializes in small satellites, has been very active in recent years in developing the technologies needed for enhanced-drag ADR, and, through the InflateSail 3U CubeSat mission, has already demonstrated the first successful disposal of a European satellite using this technique.

The development of InflateSail was supported by two European Commission (EC) (Framework Program Seven (FP7) projects: DEPLOYTECH and QB50 [5, 6].

DEPLOYTECH had eight European partners including Deutschen Zentrums für Luft- und Raumfahrt (DLR), Airbus Defense & Space (France), RolaTube Technology (UK), Netherlands Organisation for Applied Scientific Research (TNO), CGG Safety and Systems (Netherlands), the University of Cambridge (UK) and Athena Space Programmes Unit (Greece). It was assisted by NASA Marshall Space Flight Center.

The project ran from January 2012 until the end of December 2014, and its objectives were to advance the technological capabilities of three different space deployable technologies by qualifying their concepts for space use. InflateSail's ADR payload was developed through this project, and comprised two key elements: a 1m long inflatable, rigidisable, aluminium-polymer laminate mast terminated in a deployable 10m^2 four quadrant transparent polymer drag-sail supported by four Bistable Rigid Composite (BRC) carbon-fibre reinforced polymer (CFRP) booms.

By deploying the drag sail from the end of the mast (i.e. such that it is separated from the spacecraft body), the centre of mass and the centre of aerodynamic pressure of the spacecraft are separated, thereby, in principle, conveying a degree of passive stability (the weathervane effect), which in turn should maximize the structure's drag by ensuring that the sail is presented normal to the free-stream air flow (see Figures 2 and 3). One of the in-orbit test objectives of InflateSail was to observe if this actually happens in practice. The mast also ensures that the drag sail is kept clear of any host spacecraft structures which might interfere with sail deployment.

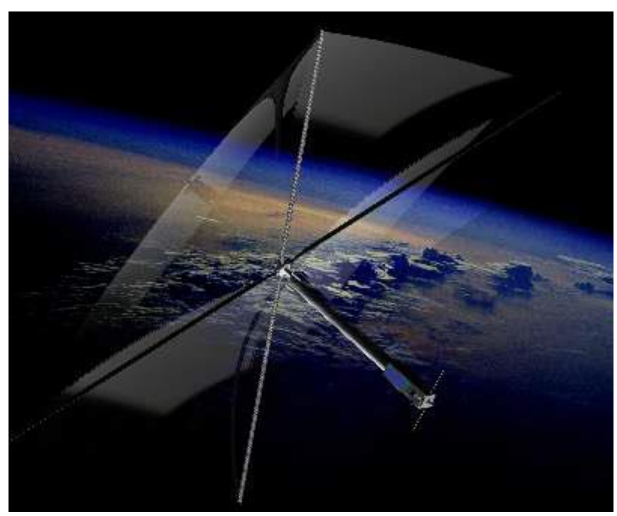

Fig. 2. Artist's Rendition of InflateSail in Orbit with the ADR Mast/Sail Payload Deployed

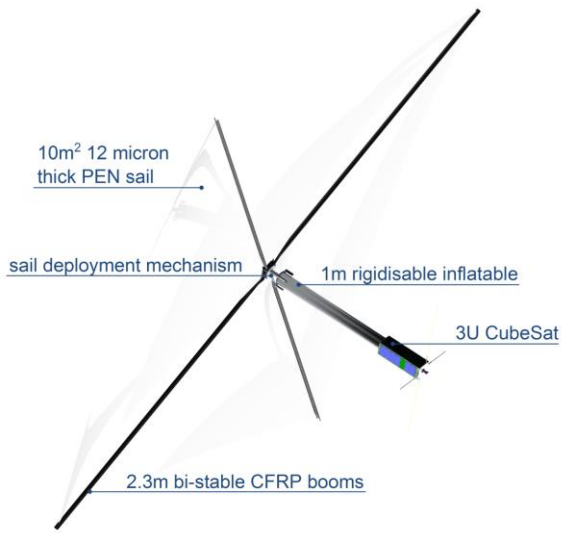

Fig. 3. InflateSail Configuration with the ADR Mast/Sail Payload Deployed

QB50, led by Von Karman Institute (VKI) Belgium, is a programme aimed at demonstrating the possibility of launching a network of 50 CubeSats built by CubeSat teams from all over the world to perform first-class science and in-orbit demonstration in the largely unexplored middle and lower thermosphere (380-200km altitude). Most of the QB50 satellites carry one of three different types of science sensor designed to investigate the thermosphere: the Ion-Neutral Mass Spectrometer (INMS), the Flux-Φ-Probe Experiment (FIPEX) and the multi-Needle Langmuir Probe (m-NLP), each developed by Mullard Space Science Laboratory (MSSL) in the UK. However, alongside these science CubeSats, there were a number of in-orbit demonstrator (IOD) CubeSat missions planned, which included the 3U InflateSail, designed and built by SSC for VKI, to carry and demonstrate, in orbit, the inflatable mast/drag-sail payload.

2. InflateSail ADR Payload and Bus Systems

Inflatesail's ADR payload occupied approximately 2U of the 3U CubeSat structure. The remaining 1U volume contained the spacecraft's core avionics stack comprising an Commercial-Off-The-Shelf (COTS) Electric Power System (EPS), a specially developed Attitude Determination and Control System (ADCS) which also doubles as the On Board Computer (OBC) (this was developed specifically for the QB50 project), a COTS VHF/UHF Transceiver (TRXVU) and bespoke Valve/Payload Controller Board (VCB) (see Figure 4).

By ensuring the spacecraft complied with the 3U CubeSat standard, it was possible to deploy it from a standard CubeSat dispenser, giving a wide choice of possible launch opportunities.

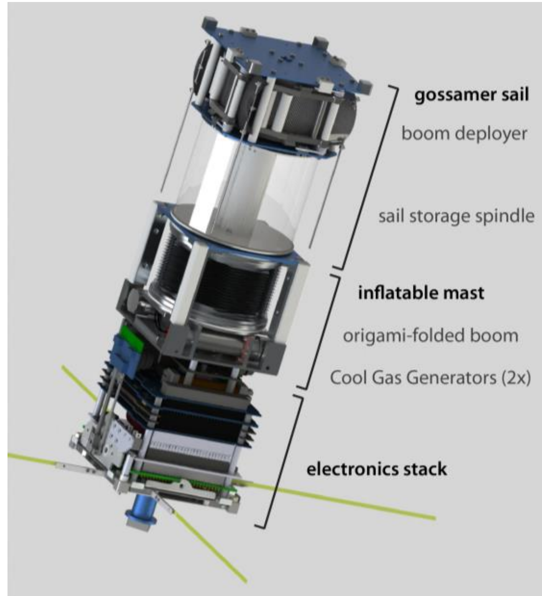

Fig. 4. CAD representation of InflateSail's Internal Layout

2.1 Inflatable Mast

The inflatable cylindrical mast consisted of a tough aluminium-BoPET (biaxially-oriented polyethylene terephthalate) polymer three-ply laminate. The two outer aluminium plies were each 13µm thick, and the central BoPET ply was also 13µm thick. The total laminate thickness, including adhesive, was 45µm.

A 12µm thick BoPET bladder was used inside the cylinder to improve air-tightness against the vacuum of space. The 1m long, 90mm diameter cylinder was inflated by a Cool Gas Generator (CGG) to a pressure of approximately 50 kPa, which was found to be sufficient to cause permanent stretching deformation in the metal plies of the laminate (see Figure 5). After inflation, the inflation gas was immediately vented in a symmetric pattern (to prevent applying a torque to the spacecraft). The resulting unpressurised rigidized cylinder has been shown to withstand compressive loads up to 50N, and bending moments up to 2Nm. Thus, the inflatable structure does not depend upon long term gas-tightness for its rigidity. Figure 6 shows the mast deployment sequence.

The fold pattern used has five faces around the circumference of the cylinder, and has a repeating unit height of 60mm (see Figures 7 and 8). When fully folded and compressed, the cylinder including its end fittings is 63mm in length (see Figure 9).

The fold pattern leaves an internal space 35mm in diameter when folded, providing storage space for an internal normally open solenoid valve.

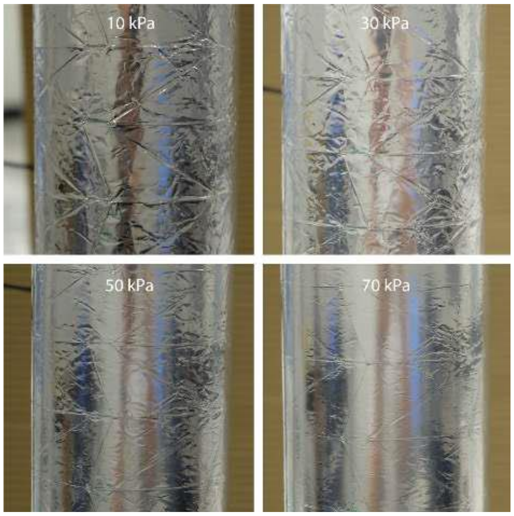

Fig. 5. Residual Creases after Depressurisation from Different Inflation Pressures (10–70 kPa)

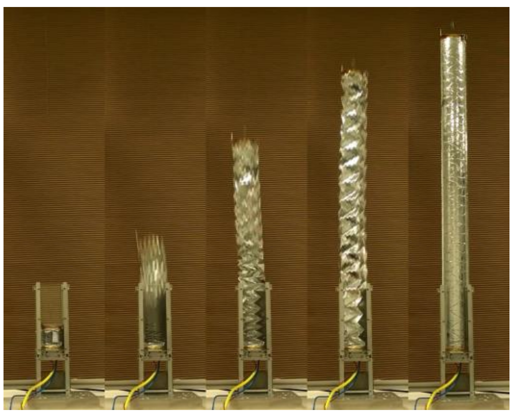
Fig. 6. The Inflatable Cylindrical Mast Deployment Sequence

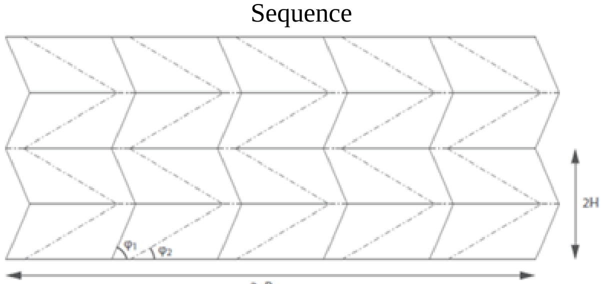

Fig. 7. The Fold Pattern Selected for the Inflatable Mast The fold pattern is fully defined by its geometric parameters n = 5, $\varphi_1 = 67^\circ$, H/R = 0.67 and R = 45mm.

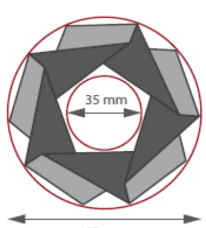

Fig. 8. Cross-Sectional View of its Fully Folded Configuration

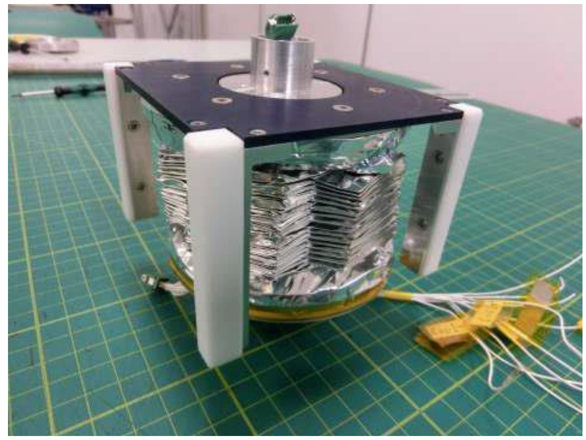
Fig. 9. The Inflatable Cylindrical Mast in its Stowed Configuration

The inflation system consists of two CGGs developed by TNO and CGG Safety& Systems BV, both located in The Netherlands [7].

The CGG provides an innovative way of storing gas by chemically binding it in a solid propellant. After ignition a self-sustained reaction passes through the grain and releases the gas at ambient temperature (hence “cool”). The remainder of the propellant is left behind in the CGG. The CGG produced for InflateSail was of a completely new design, and produces 3.9g ± 5% of nitrogen gas (equivalent to 3.2 litres at standard temperature and pressure).

The CGG itself is cylindrical with a diameter of 16 mm and an overall length of 90 mm (see Figure 10). The igniter is mounted on the top, while the gas outlet is at the bottom. After the ignition signal is given, the igniter is powered up and after a few seconds the CGG starts releasing gas. The CGG propellant is isolated from the outside atmosphere by means of a breaking foil, which ruptures when sufficient pressure is built up. The burning profile is such that 90% of the gas will be released in about 6 seconds, with 99% within 60 seconds after activation. The rapid release of inflation gas was an important design driver for the design of the inflatable boom, and was a key factor in the selection of the origami folding method to stow the boom.

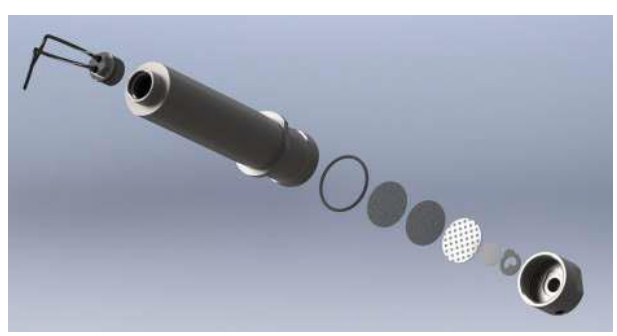
Fig. 10. Exploded View of the InflateSail CGG

The InflateSail boom is inflated directly from the CGG, and no further gas flow control is implemented. InflateSail carried two CGGs for redundancy, with each CGG capable of fully deploying and rigidizing the inflatable mast.

One of the main goals in developing this new CGG has been to avoid it receiving a pyrotechnic classification. To this end the CGG is equipped with an innovative resistance wire igniter, developed by TNO.

Another innovation has been the use of stainless steel as a construction material, instead of titanium (used for the other space qualified CGGs). Stainless steel is easier to machine and has lower material cost, but is also slightly heavier than titanium. Furthermore, the CGG is designed to be modular: its length can be adjusted to decrease or increase the amount of gas produced, without changing the ignition system or the aft part of the CGG with the gas exit.

As InflateSail was intended to demonstrate the effectiveness of this mast/sail system as a generic deorbiting system for satellites, the combination of a non-chemical rigidisation process, and a CGG based inflation system was chosen to ensure that the system could survive for many years in the pre-deployed configuration before deploying reliably at the end of a host satellite's service life. Metal-polymer laminates have been demonstrated to survive for many years in orbit, and CGGs have also been shown to function without fault after a number of years in orbit. Extensive ground testing was carried out during the development of the system to verify the system's reliability and performance in space thermal vacuum conditions [8, 9].

The Inflatable Mast layout is shown in Figure 11.

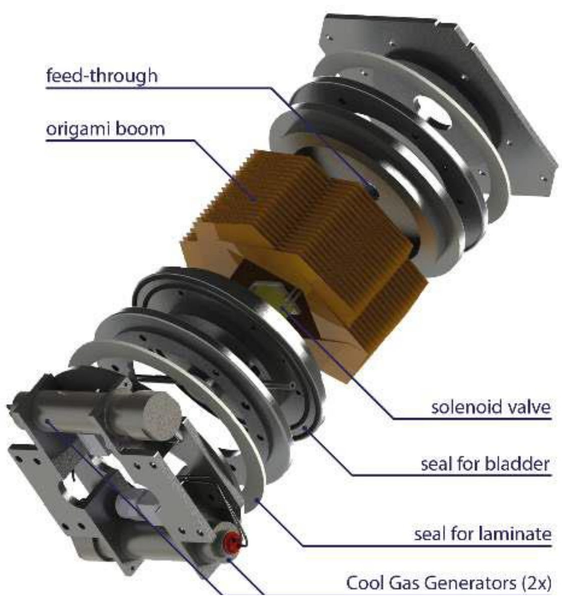

Fig. 11. Inflatable Mast System Layout

2.2 Drag Sail

The drag sail and its deployment mechanisms was developed by SSC. The sail structure consists of four separate quadrants, making up a total area of 10 m^2. The quadrants are 'Z'-folded, then wrapped around a free spinning central hub. The sail membrane is 12µm thick polyethylene naphthalate (PEN), which is naturally transparent. The membrane was deliberately left un-metallised so as to minimise perturbations from solar radiation pressure – i.e. the team wanted to observe the effects of atmospheric drag alone for comparison with the science results from the other QB50 spacecraft deployed alongside InflateSail.

There was an expectation that the lack of a metallic film as protection would mean that the polymer membrane was likely to erode quickly in the LEO environment, however, this was not thought to be a problem due to the early operations plans involving InflateSail being deployed into a very low altitude (~300km) orbit, and thus we expected it only to remain in space for a few days once the sail was deployed. However, as it turned out, the launch was changed and InflateSail was deployed into a much higher, 505km altitude Sun Synchronous Orbit (SSO), and so it remained in space for a much longer period (72 days) than was initially planned. None-the-less, the team saw no evidence that the sail was eroded, and it appeared to remain intact right up to the final orbit. However, in orbit, InflateSail was much observed to be much brighter than we expected, and from the apparent visual brightness (+4 magnitude), it is suspected that it may have become opaque (white) due to the effects of atomic oxygen in the outer atmosphere.

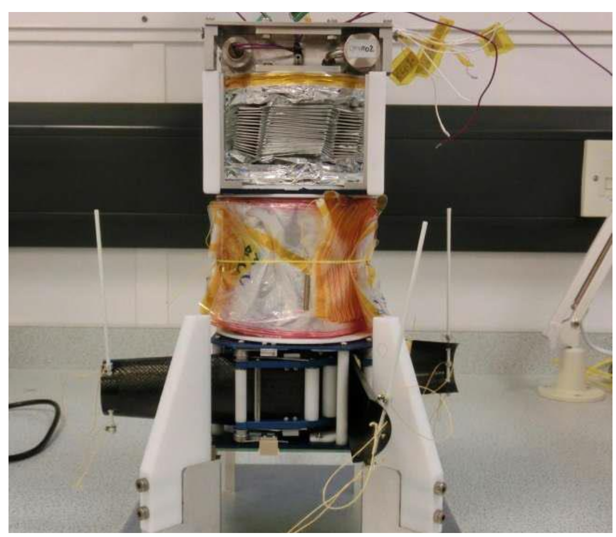

Fig. 12. The Complete InflateSail Payload Showing the CFRP Booms (bottom), the Z-Folded Sail Membrane (middle) and the Origami Folded Inflatable Mast with CGGs (top)

The sail support structure comprised four custom made CFRP bistable booms which were co-coiled just above the wrapped sail membrane (see Figure 12).

These booms, developed by a UK company: RolaTube Technology (www.rolatube.com), have the property that they are mechanically stable both in coiled and deployed modes [10]. The coiled diameter of the booms in their second, or "stowed" stable state varies along the length of the booms. This allows the booms to be stowed in their lowest possible energy state, and reduces the mass of the mechanism required to hold the coiled booms in place during launch.

The CFRP booms can be driven in and out using a precisely controlled brushless DC motor. The fully deployed sail structure is shown in Figure 13.

Fig. 13. InflateSail Inflatable Mast and Drag Sail Deployment Test

A bespoke Valve Control Board (VCB) was designed by SSC to operate the ADR payload systems.

2.3 Bus Systems

Because of the deployable nature of the payload, InflateSail required a bespoke 3U structure to be manufactured. Similarly, the solar panels had to be bespoke. Both structure and panels were designed and built at SSC, and great care was taken to make sure that the spacecraft was compliant with the QB50 launch requirements, including fitting the Innovative Solutions in Space (ISIS) QuadPack mandated for QB50.

Much of the spacecraft's avionics comprised COTS bought-in items which are in common use for CubeSat missions. For example, the electrical power system is based on the GOMspace P31u EPS, with its integral 20Whr battery. The EPS interfaces to the custom made solar panels, which are mounted with Azur Space triple-junction solar cells which have 28% efficiency.

Spacecraft communications with the ground station were executed through the COTS TRXVU Transceiver procured from ISIS. The downlink transmitter used the UHF band, whilst the uplink receiver used the VHF band. The TRXVU interfaced to the ISIS Antenna System, which comprised two deployable dipole antennas (UHF and VHF).

Internally, the spacecraft used the I2C protocol for telemetry and telecommand. All Platform subsystems communicate via I2C with the on-board computer (OBC) acting as master. The OBC is in fact also the Attitude Determination and Control System (ADCS) computer.

The ADCS unit was designed and developed by the Electronic Systems Laboratory (ESL) at Stellenbosch University and SSC at the University of Surrey specifically for the QB50 project to meet the attitude control and stability requirements of the QB50 science missions, which were to maintain the pointing of the science payloads within 10^o of the flight direction, and to provide attitude knowledge to better than 2^o precision in all axes. Table 1 gives the specifications of the unit.

Table 1. ADCS Unit Specifications

Sensors and Actuators	**Type**	**Range/ Field-of-View**	**Error (RMS)**
Magnetometer	3-Axis Magneto-resistive	±60 µT	< 40 nT
Sun Sensor	2-Axis CMOS Imager	Hemi-sphere	< 0.2^o
Nadir Sensor	2-Axis CMOS Imager	Hemi-sphere	< 0.2^o
Course Sun Sensor	6 Photo-diodes	Full Sphere	< 10^o
Rate Sensor	MEMS Gyro	±85^o/s	< 0.05^o/s
Pitch Momentum Wheel	Brushless DC Motor	±1.7 mNms	< 0.001mNms
Magnetorquers	Ferro-Magnetic Rods and Air Coil	±$0.2Am^2$	<$0.0005Am^2$ (remanence)

Fifteen ADCS units were officially supplied to the QB50 project, and it is now available commercially from Stellenbosch's spin-out company, CubeSpace.

The full QB50 ADCS unit (Figure 14) comprises:

- CubeSense
- CubeControl
- CubeComputer

These include:

- CMOS Camera Digital Sun Sensor (fine Sun Sensor)
- CMOS Camera Digital Earth Sensor
- 6 Photodiode-based Course Sun Sensors

- Micro-Electro-Mechanical-System (MEMS) Gyro
- 3-Axis Magnetoresistive Magnetometer
- 3-Axis Magnetorquer (2 Rods + 1 Air Coil)
- Pitch-Axis Small Momentum Wheel (MW)
- Optional GPS Receiver (Novatel OEM615)
- Extended Kalman Filter (EKF) Control software + SGP4 Orbit Propagator

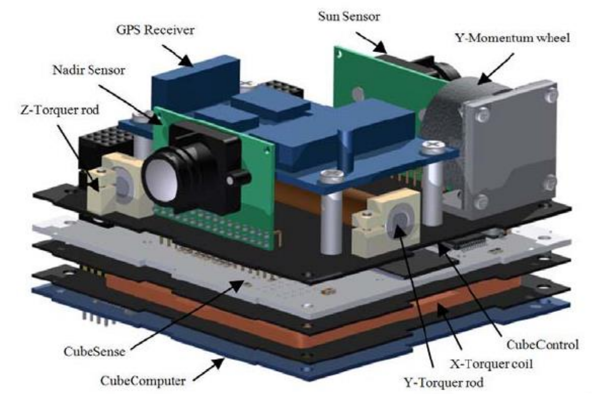

Fig. 14. QB50 ADCS Unit (Cubespace)

For InflateSail, a cut down version of the ADCS unit was flown to save volume. The pitch-axis momentum wheel and CMOS cameras were therefore removed, and instead, attitude knowledge was derived from the course Sun sensors, 3-Axis magnetometer and MEMS gyro. The GPS receiver was not fitted, however the magnetorquers were left as actuators for any attitude control needed prior to ADR payload deployment (e.g. for de-tumbling).

Figure 15 shows the InflateSail 1U Avionics Stack with and without the VCB photographed during Assembly Integration and Testing (AIT). Figure 16 shows the complete Flight Model (FM) 3U spacecraft.

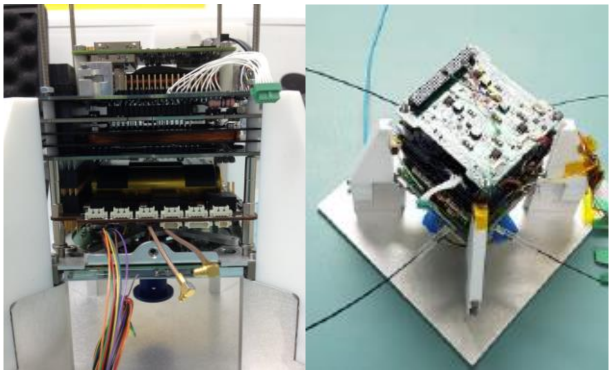

Fig. 15. (left) Inflatesail Avionics Stack Showing (top-to-bottom): QB50 ADCS Stack (before removal of the GPS and Pitch-Axis MW), GOMSpace EPS P31u with 20Whr Battery, ISIS TRXVU, ISIS Antenna Module and External 3-Axis Magnetomer; (right) Top View Showing the Valve Controller Board (VCB) and the Deployed ISIS Dipole Antennas

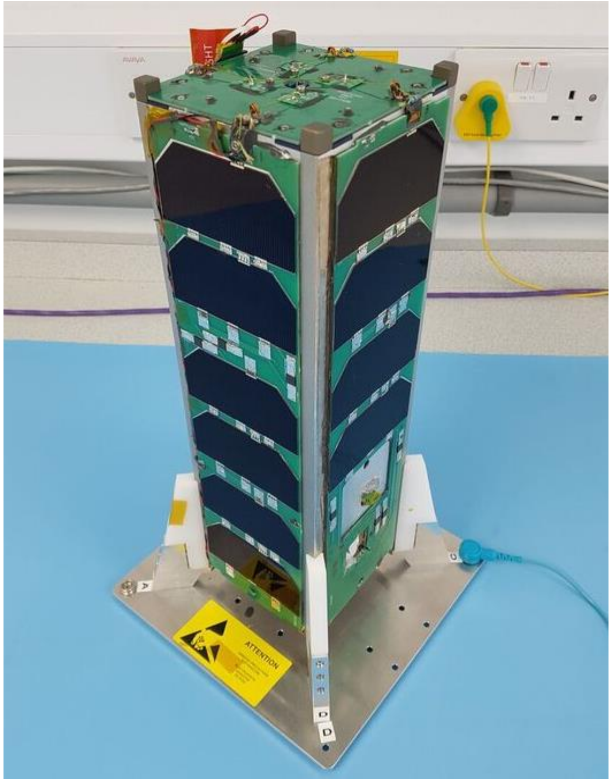

Fig. 16. InflateSail 3U CubeSat Ready for Flight

Bespoke modular flight software was written by SSC to provide full command and control and mission autonomy, whereby each module interfaces only the packet router and a hardware abstraction layer. This runs under a real-time operating system (RTOS) [11].

Each software module was contained in a separate thread or FreeRTOS task and had dedicated timing and memory allocation. Wherever possible tasks will 'suspend' and wait for an incoming message. This uses minimal processing time. Hardware level device drivers such as I2C and Controller Area Network (CAN) are handled as hardware abstraction layers (HALs) with mutexes to prevent multiple access. Priority inheritance is used to ensure low priority tasks do not block high priority tasks. Only three task priorities are given to reduce context switching between threads.

The InflateSail software has been designed such that mission success can be achieved in the event that contact with the spacecraft cannot be achieved – i.e. the spacecraft could complete its mission entirely autonomously. In addition, the hardware and firmware were configured such that success could be achieved even with the failure of the majority of the spacecraft subsystems.

2.4 InflateSail Concept of Operations

The mission concept of operations was that, once safely clear of the host launch vehicle, by stored programme command or ground command, the single deployable panel (shown on the top of the spacecraft in Fig. 16) is opened and the inflatable mast is inflated and rigidised using the CGG. The inflatable skin is a metal-polymer laminate, which gains its rigidity once deployed by a slight over-pressurisation, which also removes most of the storage creases. This "jack-in-the-box" deployment method avoids some of the complexity of a multi-panel opening design, and results in a satellite with solar cells facing in multiple directions, which is an important safety factor when the attitude is not under active control. However, this approach requires a more complicated internal structure, consisting of very smooth inwards-facing walls and a linear guide system to allow the top of the inflatable to move inside the satellite structure without twisting or rotating.

Once full mast deployment and rigidisation has occurred, the inflation gas is vented symmetrically through a valve to prevent potential destabilisation due to punctures of a still inflated structure.

The inflation of the mast pushes out the sail deployment mechanism to position it away from the body of the satellite. Once activated, a brushless DC motor, stored in the central shaft of the sail, unwinds the four lightweight bistable CFRP booms, developed by RolaTube Technology, which unfold and carry the transparent sail membrane out to its full $10m^2$ area.

The sail deployment mechanism is derived from the system described in Fernandez et al. [12], while the inflatable mast was developed specifically for InflateSail.

Once deployed, assuming the sail is presented normal to the free-stream, the ballistic ratio (mass/cross-sectional area) of the spacecraft will be dramatically reduced (from ~100 kgm^{-2} to ~0.2 kgm^{-2}), and the resulting increase in aerodynamic drag forces will cause the spacecraft to lose altitude until re-entry (and destruction) is achieved.

This sequence of events is pre-programmed to occur automatically, controlled by a count-down timer, unless it is held off by ground command. Thus, if ground command is not available or lost, the sequence will trigger after a set time. The automatic sequencing is set such that, even if it is triggered, deployment of the ADR payload cannot occur before the spacecraft is well clear of the host launch vehicle.

3. InflateSail Assemblt Integration and Testing

Using mechanical computer aided design (CAD), a complete payload/bus system layout was designed, and the avionics stack and ADR payload appeared to fit the bespoke 3U structure. However, when practical assembly first took place, it became clear that the clearances were too tight, and that some stripping of components from the bus would be necessary. This was when many of the superfluous items in the ADCS unit were removed. The team also took the opportunity to re-examine the payload controller board, and decided that a new version – the Valve Controller Board (VCB) – would offer higher reliability, even though the previous version had performed well in ground tests. The payload retention strategy was also re-examined, to ensure that the inflateable mast would deploy smoothly.

As a result of these late design changes in the summer of 2016, an accelerated programme of final assembly integration and testing (AIT) and environmental testing (EVT) was carried out between November 2016 and April 2017, including vibration, shock, thermal-vacuum and magnetic cleanliness tests as well as RF communications tests and full system end-to-end testing with the SSC ground-station. One of the lessons learnt from the QB50 project was that such thorough testing is a necessary requirement to ensure full mission success.

The team finished testing InflateSail (See Figure 17) and it was successfully delivered to ISIS (Innovative Solutions in Space) in the Netherlands on 10th April 2017 and integrated into its QuadPack launch Pod on 12th April 2017 (Figure 18).

Fig. 17. InflateSail Team with InflateSail Complete and Ready for Delivery

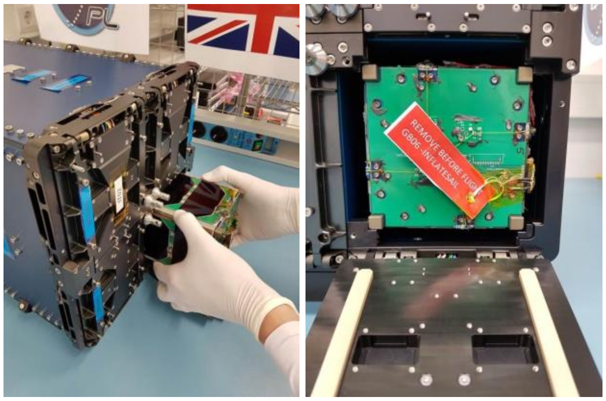

Fig. 18. InflateSail Being Integrated into the ISIS QuadPack

4. InflateSail Launch and Results

InflateSail was launched on Friday 23rd June 2017 at 3.59 am UTC into a 505km altitude, 97.44° inclination SSO. It was one of 31 satellites that were launched simultaneously on the PSLV (polar satellite launch vehicle) C-38 from Sriharikota, India.

The first data were received at 09:35am BST (08:35 UTC) on InflateSail's very first pass over Surrey (Figure 19).

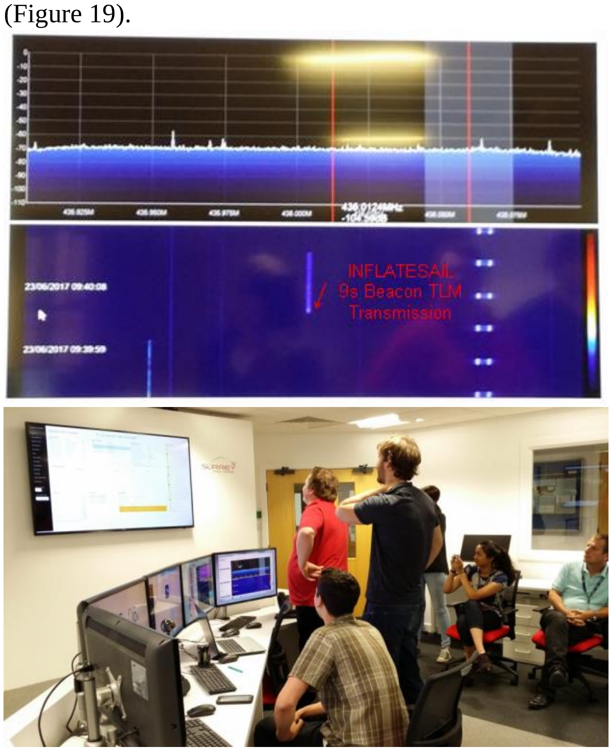

Fig. 19. InflateSail's First Pass over the Surrey Space Centre Ground-Station: (top) Spectrum Analyser Screen Showing the Expected 9s Telemetry Beacon Transmissions; (bottom) InflateSail Team Monitoring the First Real-Time Telemetry Data

The spacecraft had been pre-programmed to transmit a beacon signal for 9 seconds every minute, carrying key system telemetry data. The beacon was exactly on the predicted frequency and our automatic demodulation/decoding systems produced excellent telemetry from the strong signal.

A quick analysis of the real-time telemetry data from the first passes showed the spacecraft to be in good health – the battery voltage, solar array currents, solar cells charging currents and transmitter powers and reflected powers were all nominal, and the spacecraft rotation rates looked to be very modest ~0.5 revolutions per minute or ~3 degrees per second (see Figure 20).

Internal temperatures were good – ranging from a cold limit of ~ - 2°C to a warm limit of ~20°C.

3.1 InflateSail Attitude Dynamics

Figure 21 shows InflateSail's axis system. The mast and sail deploy from the +X facet and the X-Axis is the mast axis, normal to the sail.

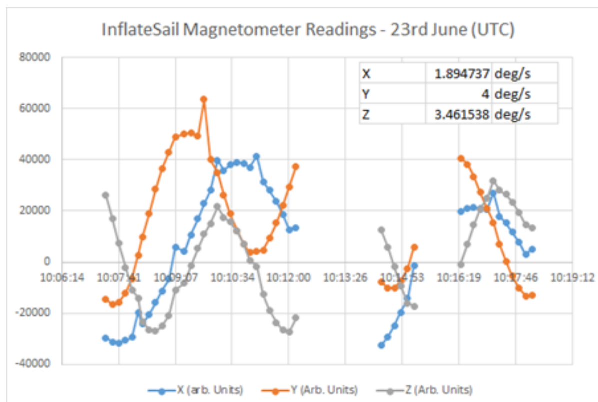

Fig. 20. Initial Magnetometer Data (2nd Pass)

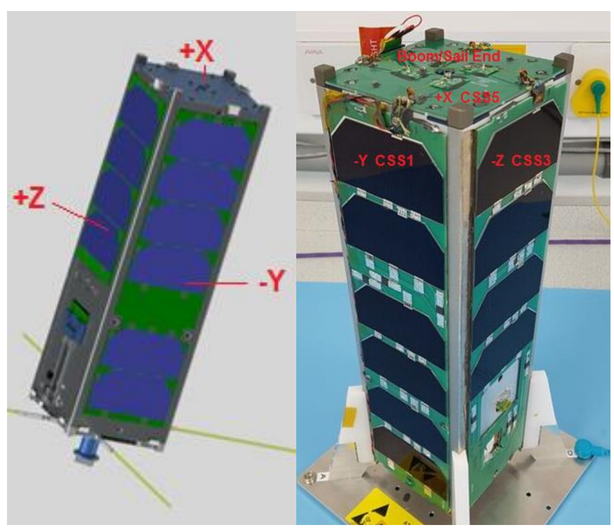

Fig. 21. InflateSail's Axis System and CSS Locations

The locations of the CSS photodiodes are given in Table 2.

Table 2. Coarse Sun Sensor Layout

Sensor Number	**Axis**
CSS1	-Y
CSS2	+Y
CSS3	-Z
CSS4	-X (Mast Axis – Dipole Antennas Side
CSS5	+X (Mast Axis – Deployed ADR Mast/Sail Side
CSS6	+Z

The slow rotation rates indicated by the by the magnetometer data were confirmed by observing the results from the six Coarse Sun Sensors (CSSs).

Figure 22 shows the CSS readings from the first pass (08:34 to 08:43 UTC – 9 minutes). The scale is in raw 8-bit output units: 0 – 255. CSS2 (+Y) (black) and CSS3 (-Z) (orange), in particular, show a classic truncated sinusoidal variation, 90^{o} out of phase, as would be expected.

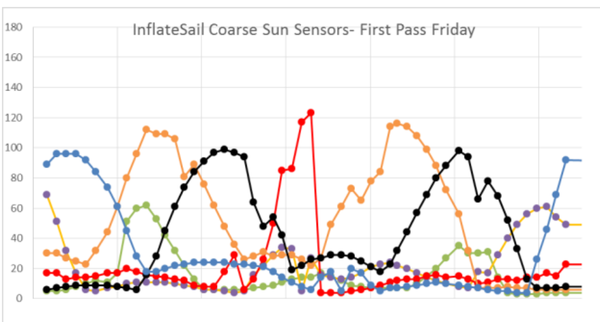

Fig. 22. Coarse Sun Sensor Data (1st Pass: 08:34 to 08:43 UTC Friday 23rd June 2017)

Our conclusion from these results, taken just a few hours into the mission, was that Inflatesail was in good health, and was in a relatively slow but rather complex rotation primarily about the X-axis.

Analysis of other telemetry indicated that there had been a single un-commanded OBC reset event recorded after deployment but before the first pass over SSC. Over the following weekend (24th-25th June) there was one more. These were in addition to the pre-programmed once-per-day resets, designed to activate the mast/sail after a fixed period.

If certain timing conditions applied during these un-commanded resets, then there was a possibility that the automatic deployment sequence may have already been activated before the OBC could recover to suppress it.

The slow rotation rates we measured, and the high B* value (drag) of "Object F" (see Figure 23) compared to all the other spacecraft deployed from that launch indicated that this indeed had happened – 50-60 minutes after ejection from the launch pod and around three hours before the first pass over Surrey.

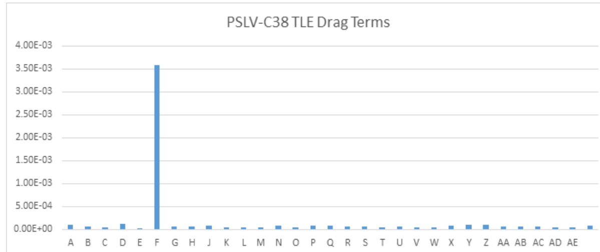

Fig. 23. B* Drag Terms from the Two Line Element (TLE) Sets for the Spacecraft Reseased from the PSLV-C38 Launch. Object "F" is Noticeably Different and was Later Confirmed to be InflateSail.

The ADR system was due to be automatically commanded to deploy on Tuesday 27th June and looking at the CSS telemetry for that day (Figure 24), it can be seen that there is a steady, slow rotation showing up in all CSS sensors, except CSS4 (green) which is partly occluded by one of the antenna hinges.

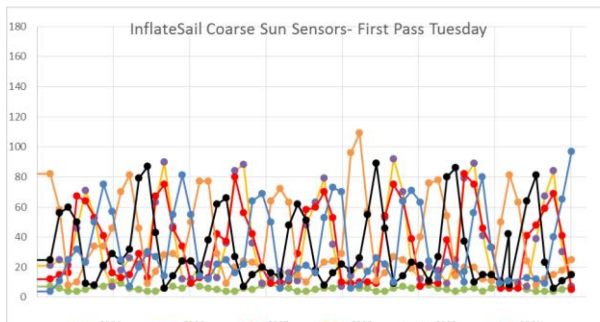

Fig. 24. Coarse Sun Sensor Data (08:56 to 09:06 UTC Tuesday 27th June 2017)

We had programmed the deployment sequence such that the first activation would only extend the sail booms to 70% of their final length. The second activation would then complete the extension to 100%, leading to the sail spreading to its full 10m^2 area.

We would expect, then, to see a signature of the resultant change in the inertia tensor showing up in the rotation rate data, and this is indeed the case as shown by analysis of CSS5 data (see Figure 25). This confirmed that the second deployment had taken place.

From an initial rate of -3.4^{o}/s with the sail at 70% extension on 23rd June, we saw the rate *increase* steadily to -4.2^{o}/s by the 27th June, just before the second activation took place (note Figure 25 shows this as a downward trend). Upon 100% sail extension, the X-Axis rotation rate *decreased* (as one would expect from the increased X-axis moment of inertia) and returned to approximately -3.4^{o}/s. Over the next two weeks the rate increased again, before finally settling to around -4.0^{o}/s for the rest of July.

Apart from the step change decrease in X-axis spin due to the sail deployment, these early X-axis spin increases appear to show a transfer of angular momentum to the maximum moment of inertia axis – i.e. the X-axis. We suspect that this happens because of the flexible nature of the mast/sail structure, allowing such behaviour to occur.

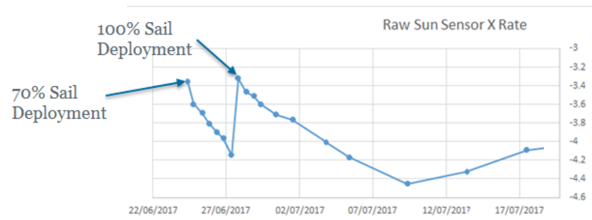

Fig. 25. X-Axis Spin Rate as Determined from CSS5 (note the scale (^{o}/s) is negative)

The ADCS unit provides its own independent estimate of the body rates by on-board analysis of the ADCS sensor data. Figure 26 shows these estimates over the mission lifetime.

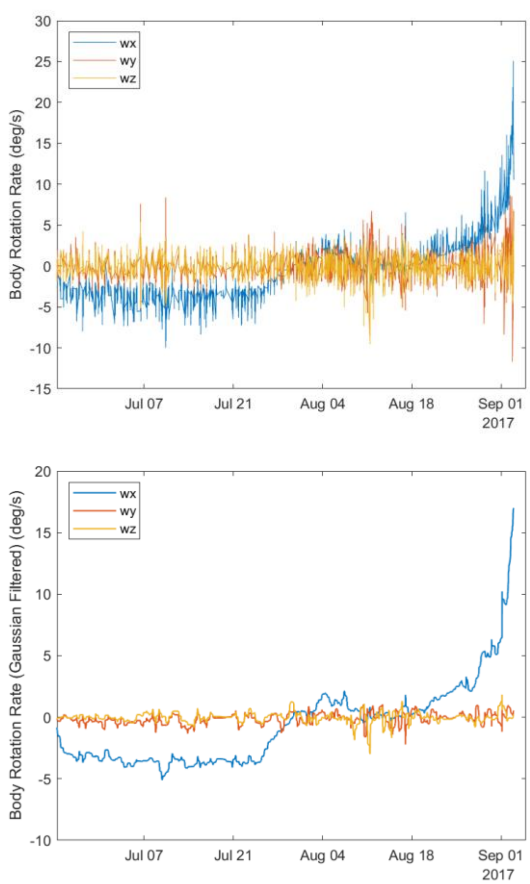

Fig. 26. ADCS Internal Body Rate Estimator Data (top) Raw; (bottom) Smoothed

The body rate rotations for the Y-Axis (orange) and Z-Axis (yellow) are very small indeed – close to zero degrees per second. The X-Axis body rate (blue) is seen to increase initially to around -4^o/s and stay there until the last week in July, when a steady decrease in X-rate occurs, approaching near zero for most of August. In mid-to-late August the body motion becomes complex – but everything happens at a slow rate. Beyond ~20th August, the X-rate gradually increases (positively) until re-entry occurs. We last record it at being around +20^o/s. It should be noted that the body-rate estimator error bars are quite large for such slow rates ~ ±2^o/s for the raw values and ~ ±0.5^o/s for the smoothed values.

We interpret these body dynamics as being due to the increasing effect of atmospheric density as the satellite falls. A distinct change in body dynamics – possibly due to increasing Weathervane stability – seems to occur around the end of July, when the spacecraft has dropped to ~470km altitude. The body rates essentially go to zero.

From late August, when the satellite dropped below 450km, the increasingly positive X-Axis body rate seems to indicate a "wind-milling" effect – that is the satellite is spinning increasingly rapidly about the mast, normal to the sail, with the sail quadrants acting like the sails of a windmill. The phenomenon continues at increasing rate until contact was lost at ~250km altitude.

3.2 InflateSail Obital Dynamics

During the first few days of monitoring, it became very clear that Inflatesail was behaving differently to the other CubeSats realeased from the PSLV C-38 launch in terms of its orbital dynamics. It was observed to be dropping rapidly and accelerating ahead of the others.

Figure 27 shows the drop in perigee altitude (as determined from the TLE sets provided by the North American Aerospace Defense Command – NORAD). The rapid descent of InflateSail (orange) compared to the others is clear. The step changes in descent rate are related to space weather phenomena – particularly noticeable for mission day ~23 (15th July) following an M2 class solar flare on 14th July 2017.

Figure 28 shows that the orbital eccentricity behaviour of InflateSail was also very different to that of the other spacecraftlaunched on PSLV C-38.

Initially eccentricity was increasing for InflateSail more rapidly than for the others, and then there was a step drop on day 23 carresponding to the effects of the solar flare. As InflateSail dropped below 480km, the eccentricity reduced. Indeed, eccentricity is expected to decrease due to drag as, although the drag force is strongest at perigee, the effect shows up as a drop in apogee height half an orbit later – thus perigee drops a small amount, but apogee drops by a greater amount, causing the orbit to become more circular.

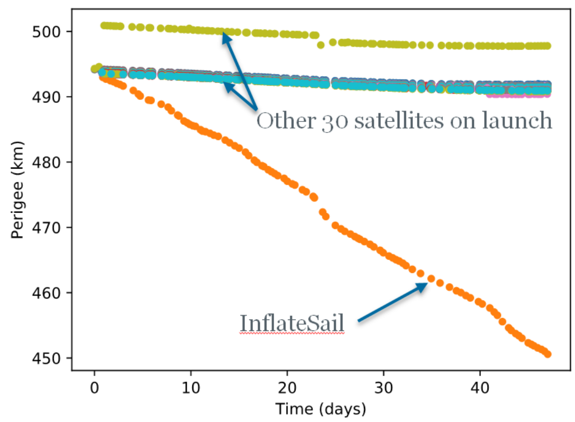

Fig. 27. Perigee Altitude of the PSLV C-38 Satellites (InflateSail = Orange)

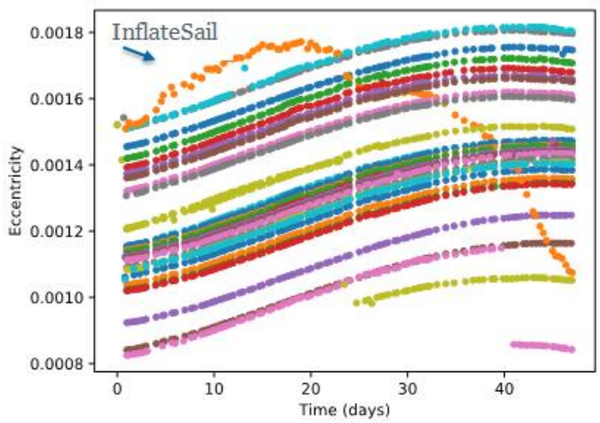

Fig. 28. Orbital Eccentricity of the PSLV C-38 Satellites (InflateSail = Orange)

We believe that the initial increase in eccentricity may be due to diurnal factors (atmospheric heating during sunlit hours) interacting with the SSO.

Figure 29 shows the B* drag term for the PSLV C-38 satellites. The drag is much greater for InflateSail (orange) than for the others. The variation in B* correlates very well with the National Oceanic and Atmospheric Administration's (NOAA's) geomagnetic indices – i.e. the effects of space weather show up very clearly on the orbital behaviour of InflateSail.

The mast/sail ADR system proved itself to be very effective, and InflateSail dropped from 505km to re-entry (250km) in just less than 72 days. InflateSail came down over South America at 01:27 UTC (±6 minutes) on 3rd September 2017. The last radio contact appears to have been with the SSC ground-station at 21:17 UTC on 2nd September 2017.

Figures 30, 31 and 32 show the complete orbital history of the InflateSail Mission derived from NORAD TLEs. Data for the URSA-MAIOR QB50 3U CubeSat, launched alongside InflateSail are shown for comparison. This illustrates that, without the ADR payload, InflateSail would hardly have changed altitude.

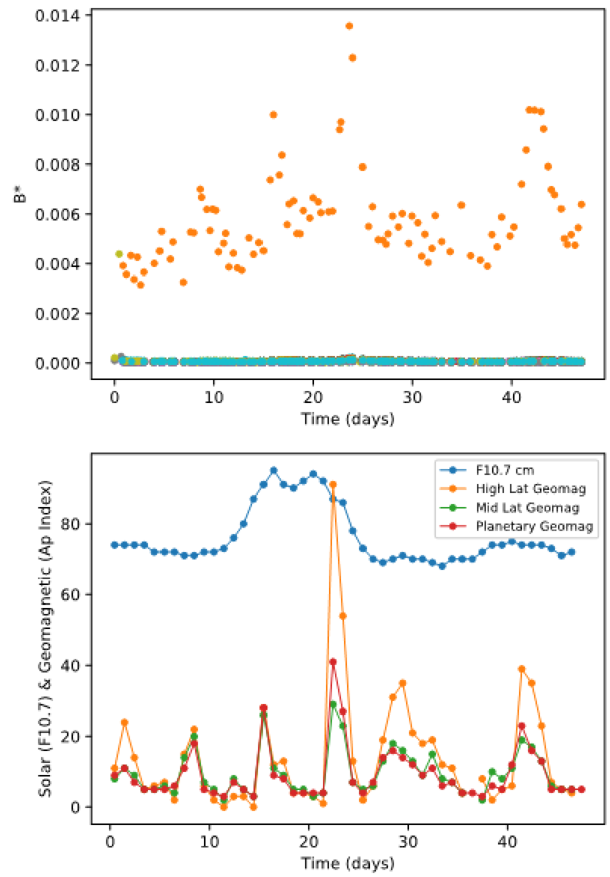

Fig. 29. (top) B* Drag Term (orange = InflateSail); (bottom) Space Weather Indices from NOAA

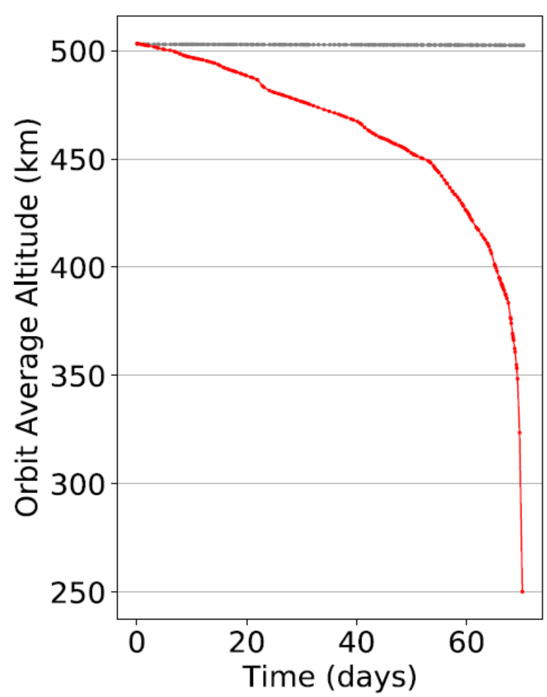

Fig. 30. Orbit Average Altitude (InflateSail = red, URSA-MAIOR = grey)

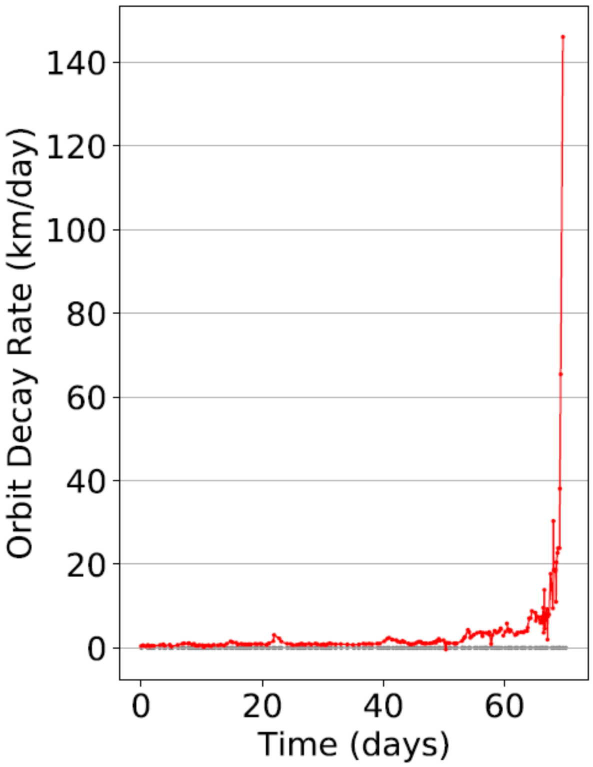

Fig. 31. Orbital Decay Rate
(InflateSail = red, URSA-MAIOR = grey)

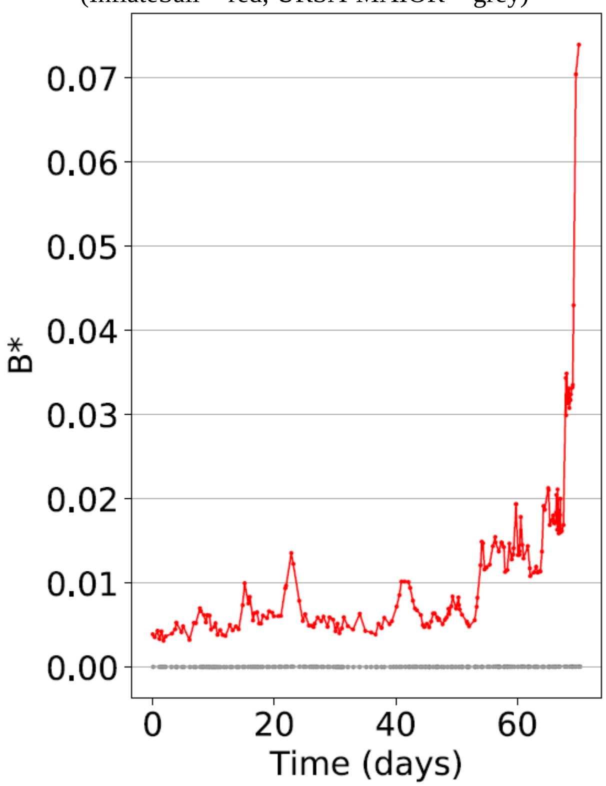

Fig. 31. B* Drag Term
(InflateSail = red, URSA-MAIOR = grey)

3.3 Visual Sightings

InflateSail was a 3U CubeSat with a 1m long metallised mast and a $10m^2$ transparent polymer sail. As such, we were not expecting it to be visible to the naked eye, however, to our surprise, it was seen and tracked by observers around the world.

For example, Thomas Dorman posted on-line a digital image taken on 12th July 03:39 UTC. He used a Sony WSC w-5 camera with a 30 second exposure (ISO400) and reported a visual magnitude of +4.2 (Figure 32).

Similarly the URSA-MAIOR team at La Sapienza University, Rome, captured an image of InflateSail and reported a magnitude of +4 (Figure 33).

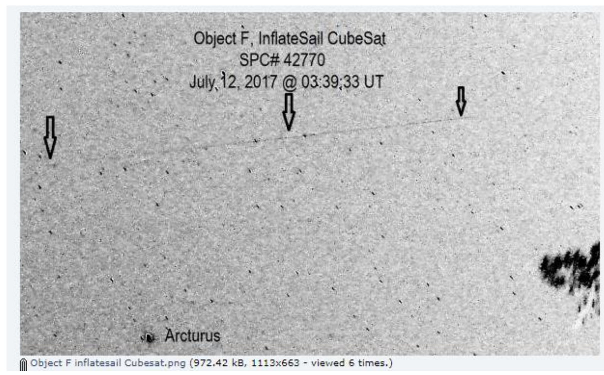

Fig. 32. Ground Image of InflateSail in Orbit (Inverted Grey-Scale) (Courtesy of Thomas Dorman) https://forum.nasaspaceflight.com/index.php?topic=41762.260

We suspect that the apparent brightness of InflateSail may have been due to the sail being affected by atomic oxygen and turning opaque (white). There was no evidence for any other degradation of the sail.

Fig. 33. Ground Image of InflateSail in Orbit (Courtesy of Fabrizio Piergentili and Tommaso Cardona at La Sapienza University, Rome)

4. Future Applications

The ADR payload of InflateSail is seeing reuse on the RemoveDebris mission, which was launched to the ISS in April 2018.

RemoveDebris is an EC FP7 supported project led by SSC, to produce a low cost mission performing key ADR technology demonstrations, including the use of a net, harpoon, vision-based navigation (VBN) system and a drag-sail, in a realistic space operational environment.

For the purposes of the mission, two CubeSats will be ejected and used as the targets for experiments instead of targeting real space debris [12].

The craft was launched to the ISS on the 2nd of April 2018, on board a Dragon capsule (SpaceX CRS-14 ISS re-supply mission). From here the satellite was deployed via the NanoRacks Kaber system mounted on ISS's Canadarm-2 into an orbit of around 400 km altitude on 20th June 2018.

One of the target "debris" CubeSats (DebrisSat-1) makes use of the same inflateable mast system as that demonstrated on InflateSail to increase its size to approximately 1m diameter. This will be used for demonstration of a net-based capture system. The DebrisSat-1 CubeSat is shown in Figure 34 in its stowed and deployed states.

The $10m^2$ drag-sail embarked on the host RemoveDebris spacecraft is identical to that on the InflateSail CubeSat, albeit with a metalised rather than transparent sail, suitable for the longer expected mission duration. The Sail deployer has electrical and mechanical interfaces appropriate for the Micro-Sat host. This is shown in Figure 35.

Having demonstrated the behaviour of a sail fitted to a low mass CubeSat on InflateSail, RemoveDebris will demonstrate its performance on a 100kg class Micro-Sat, developed by Surrey Satellite Technology Ltd (SSTL) as a further confidence building step towards full commercialisation. It is anticipated the sail will reduce the time to de-orbit RemoveDebris from ~2 years to approximately 3 months.

In general, drag-sails are a useful technology to mitigate space debris by disposal of satellites at end of their mission lifetime. Figure 36 shows the performance of a $10m^2$ sail on a typical 100kg class Micro-Sat as time to deorbit vs. orbital altitude, as modelled using STELA model from CNES [13].

Performance is shown for the case where the spacecraft is freely tumbling with no attitude control, and also for the case of a spacecraft that remains active and therefore is able to orient itself and the sail to maximize the drag area.

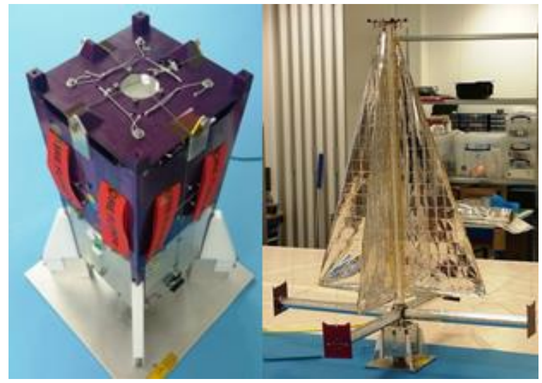

Fig. 34. RemoveDebris DebrisSat-1 CubeSat in Stowed (left) and Deployed (right) States

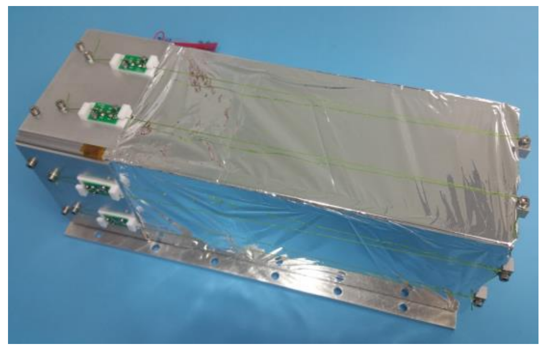

Fig. 35. RemoveDebris Drag-Sail Payload

It can be seen that a drag-sail system can expedite the re-entry of a satellite, but also to allow launch into a higher altitude orbit, whilst retaining compliance with the Inter-Agency Space Debris Coordination Committee (IADC) guidelines stipulating a 25 year lifetime. An increase in initial mission orbital altitude from 610km to 800km is possible through use of a system constituting ~3% spacecraft total mass. Larger sail systems can be embarked making use of the same technologies.

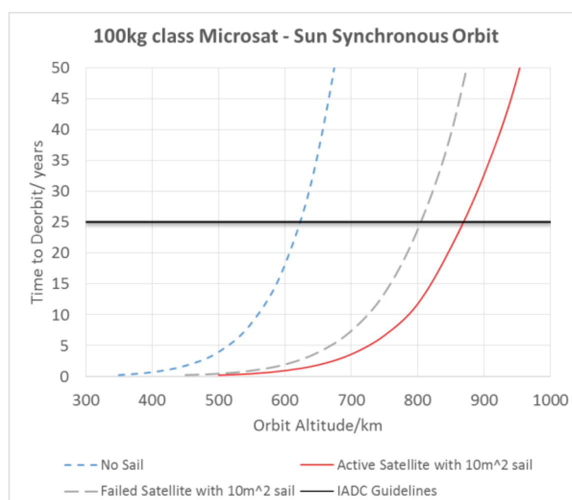

Fig. 36. Performance of a $10m^2$ Drag-Sail Mounted on a 100kg Micro-Sat

5. Conclusions

InflateSail has been a highly successful mission, which has demonstrated the practicality of using drag augmentation to actively de-orbit a spacecraft. The inflatable mast/drag-sail technology developed by SSC will next be used on the RemoveDebris mission, launched in 2018, which will demonstrate the capturing and de-orbiting of artificial space debris targets using a net and harpoon system. These are steps towards the full commercialisation of a practical, cost-effective and reliable ADR system for LEO spacecraft – especially for those in the sub 500kg class, where destruction in the atmosphere is complete, and the risk of ground impact is negligibly small.

Acknowledgements

The authors acknowledge the help and support of many people who have made this mission possible, in particular our fellow team members in the DEPLOYTECH and QB50 FP7 projects, not least our colleagues at the Von Karman Institute (VKI), who managed and led the highly ambitious QB50 project.

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